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Topical Results on Vector-Meson Production from the HERA Collider Experiments^a

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The HERA collider experiments H1 and ZEUS have established extensive measurement programs for diffractive vector-meson production processes during the first six years of their operation. The results provide stringent phenomenological tests of quantum chromodynamical descriptions of hard diffraction. We discuss recent topical results on Υ photoproduction, on decay-angle analyses of ρ^0 , ϕ and J/ψ electroproduction and on ρ^0 and ϕ photoproduction at high momentum transfer.

1 Introduction

The HERA collider experiments H1 and ZEUS have developed measurement programs of diffractive vector-meson production in electron-proton collisions, extending the rich history of such investigations in the 1960s and 1970s to the modern era. Many of the topics addressed by the data have as sole precedent investigations performed before the development of quantum chromodynamics as the fundamental theory of the strong interaction. As a result, recent years have witnessed rapid expansion in a field of study in which the predictions of an asymptotically free field theory are tested for the first time in new domains of energy and photon virtuality. In light of the recent impressive theoretical successes in describing hard diffractive phenomena, in particular the factorization theorems proven for exclusive[?] and semi-exclusive[?] vector-meson production, these new measurements are providing an extensive phenomenology useful in testing the precepts of quantum chromodynamics in their application to diffractive processes.

In this report, we discuss three topics of particular interest to this workshop: the first measurements of Υ photoproduction, the results on the helicity structure of ρ^0 , ϕ and J/ψ electroproduction and the semi-exclusive photoproduction of ρ^0 and ϕ mesons at high momentum transfer.

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2 Υ Photoproduction

In stark contrast to the first published observation of photoproduction of the J/ψ meson a few months following its discovery in 1974, twenty years passed between the discovery of the Υ meson and the first report of its production in photon-proton interactions by the ZEUS experiment in 1997.[?] This measurement of exclusive Υ photoproduction at a photon-proton center-of-mass energy, W , of 120 GeV, has since been confirmed by the H1 collaboration, who have released a preliminary result[?] for the cross section at $W=160$ GeV. Each experiment identifies the Υ family via a resonant structure in the observed dimuon mass spectrum, which is dominated by the the continuum background from the Bethe-Heitler pair-production process. Figure 1 shows the preliminary measurement of this mass spectrum reported by H1. The H1 spectrum shows a peak which leads to an estimated signal of 8.3 ± 3.9 events. The mass resolution provided by the central tracking chambers and magnetic field does not allow the separation of the Υ , Υ' and Υ'' in either of the experiments, requiring the use of estimates of their relative production in order to extract

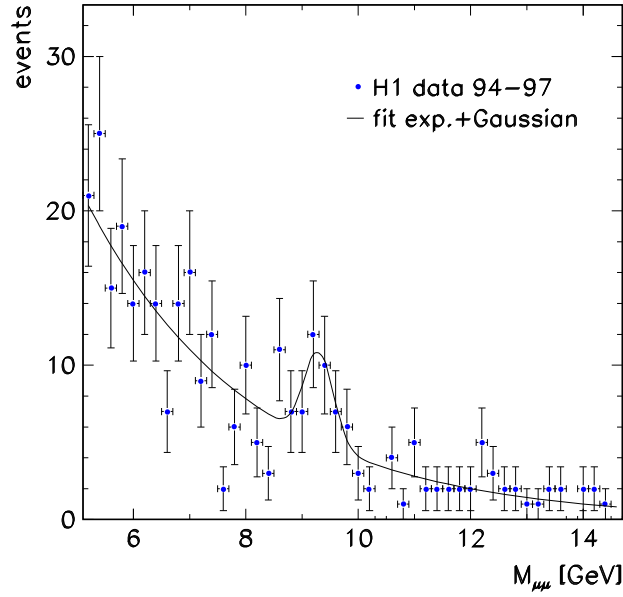


Figure 1: Invariant mass spectrum for diffractively photoproduced muon pairs reported by the H1 collaboration.[?] The curve shows the result of a fit to a sum of exponential and Gaussian functions

a production cross section for the Υ alone. The resulting determinations of the cross section for the exclusive process $\gamma p \rightarrow \Upsilon(1S)p$, shown in Fig. 2, exceed the leading-order QCD estimate[?] by a factor of 5-10. Detailed theoretical

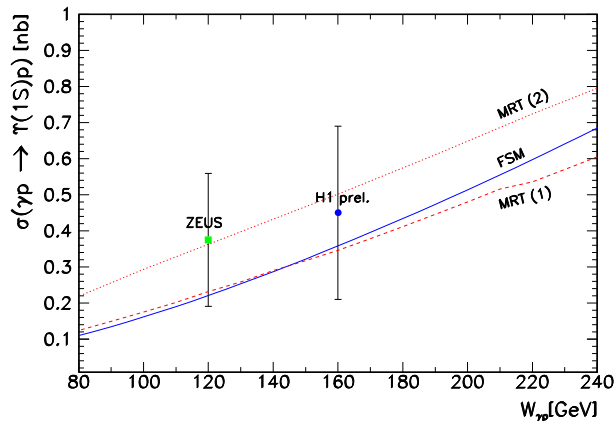


Figure 2: Measurements from the H1 and ZEUS collaborations of the elastic $\Upsilon(1S)$ photoproduction cross section. The error bars show the quadratic sum of statistical and systematic uncertainties. The curves show the results of QCD-based calculations which take into account a variety of effects beyond leading order[?]

investigations[?] into reasons for the large cross section have emphasized the importance of the evolution of the parton density functions (which are necessarily skewed by the kinematic lower bound on the momentum transferred to the proton resulting from the rest mass of the $\Upsilon(1S)$) and that of the contribution from the real part of the amplitude.

These initial measurements establishing the large cross section were based on an integrated luminosity of about 40 pb^{-1} for each experiment. The HERA luminosity upgrade program and operation schedule through 2005 will permit an increase in the Υ candidate event sample of at least a factor of twenty and is likely to enable decay-angle studies of the type described below for the lighter vector mesons.

3 Helicity Analyses of ρ^0 , ϕ and J/ψ Electroproduction

The simplicity of the final state in the exclusive production of vector mesons permits detailed investigations of the decay-angle distributions, which have provided much information on the helicity structure of the diffractive production mechanism. These analyses of the decay-angle distributions have been

employed as a means of measuring the ratio of the cross sections for longitudinal and transverse photons, R . This type of study provided another early success of the perturbative QCD models of exclusive diffractive processes by verifying the prediction that the longitudinal cross section exceed the transverse cross section at high Q^2 .

Three angles suffice to completely describe the exclusive electroproduction of vector mesons, as shown in Fig. 3 for the example of ρ^0 production: the azimuthal angle between the scattering plane and the production plane, Φ_h , and the two ρ^0 decay angles: ϕ_h , the azimuthal angle between the production

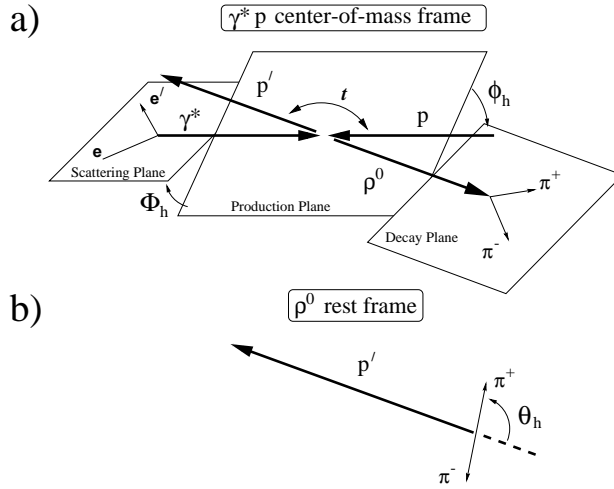


Figure 3: Schematic diagram of the process $ep \rightarrow e\rho^0 p$ (a) in the virtual-photon/proton center-of-mass system, and (b) in the rest frame of the ρ^0 meson

and decay planes, defined in either the virtual-photon/proton system or in the ρ^0 rest frame, and θ_h , which is the polar angle of the positively charged decay product, defined with respect to the direction of the ρ^0 momentum vector in the virtual-photon/proton system, which is opposite to the momentum vector of the final-state proton in the rest frame of the ρ^0 meson. This latter choice of spin-quantization axis defines the helicity frame, in which helicity conservation was found to hold approximately in exclusive ρ^0 photoproduction experiments at SLAC in the early 1970s.^{?,?}

Following the work of Schilling and Wolf,[?] the three-dimensional angular distribution for this decay of a spin-1 state to two spinless particles has been

parameterized as follows:

$$\begin{aligned}
W(\cos \theta_h, \phi_h, \Phi_h) = \frac{3}{4\pi} \bigg[& \frac{1}{2}(1 - r_{00}^{04}) + \frac{1}{2}(3r_{00}^{04} - 1) \cos^2 \theta_h \\
& - \sqrt{2} \operatorname{Re}\{r_{10}^{04}\} \sin 2\theta_h \cos \phi_h - r_{1-1}^{04} \sin^2 \theta_h \cos 2\phi_h \\
& - \epsilon \cos 2\Phi_h (r_{11}^1 \sin^2 \theta_h + r_{00}^1 \cos^2 \theta_h - \sqrt{2} \operatorname{Re}\{r_{10}^1\} \sin 2\theta_h \cos \phi_h \\
& \quad - r_{1-1}^1 \sin^2 \theta_h \cos 2\phi_h) \\
& - \epsilon \sin 2\Phi_h (\sqrt{2} \operatorname{Im}\{r_{10}^2\} \sin 2\theta_h \sin \phi_h + \operatorname{Im}\{r_{1-1}^2\} \sin^2 \theta_h \sin 2\phi_h) \\
& + \sqrt{2\epsilon(1+\epsilon)} \cos \Phi_h (r_{11}^5 \sin^2 \theta_h + r_{00}^5 \cos^2 \theta_h \\
& \quad - \sqrt{2} \operatorname{Re}\{r_{10}^5\} \sin 2\theta_h \cos \phi_h - r_{1-1}^5 \sin^2 \theta_h \cos 2\phi_h) \\
& + \sqrt{2\epsilon(1+\epsilon)} \sin \Phi_h (\sqrt{2} \operatorname{Im}\{r_{10}^6\} \sin 2\theta_h \sin \phi_h \\
& \quad + \operatorname{Im}\{r_{1-1}^6\} \sin^2 \theta_h \sin 2\phi_h) \bigg], \tag{1}
\end{aligned}$$

where the superscripts of the combinations of spin-density matrix elements correspond to the helicity degrees of freedom of the virtual photon, and the subscripts to those of the dipion state. The fifteen coefficients r_{ik}^{04} , r_{ik}^α are related directly to various combinations of the helicity amplitudes, $T_{\lambda_\rho \lambda_\gamma}$, where λ_ρ and λ_γ are the helicities of the ρ^0 meson and of the photon, respectively. The assumption that helicity is conserved in the photon/vector-meson transition when the amplitudes are defined in the helicity frame (“s-channel helicity conservation” or “SCHC”), with the consequence that the degree of ρ^0 polarization is equal to the ratio of the longitudinal and transverse cross sections, allows the extraction of this ratio R from the distribution in polar angle alone. A compilation of determinations of R via this method is shown in Fig. 4. The data from the fixed-target muon experiment at FNAL, E665,[?] and the low- Q^2 data from the ZEUS collaboration identify a region of transition to increasing values of R , with the longitudinal cross section becoming dominant for $Q^2 \gtrsim 2 \text{ GeV}^2$. Together with the latest results from the H1 collaboration,[?] these data indicate that the value of R reaches a plateau for $Q^2 \gtrsim 5 \text{ GeV}^2$.

The H1[?] and ZEUS[?] collaborations have recently completed analyses of the three-dimensional angular distribution for data samples of a few thousand events, extracting the fifteen coefficients r_{ik}^{04} , r_{ik}^α . Figure 5 shows the results from the ZEUS collaboration in the kinematic region $3 < Q^2 < 30 \text{ GeV}^2$, $40 < W < 120 \text{ GeV}$ and $|t| < 0.6 \text{ GeV}^2$, comparing them to the results from the H1 collaboration in a similar kinematic region, and to a calculation by Ivanov and Kirschner[?] (solid line). The inner error bars represent the statistical uncertainty; the outer error bars show the quadratic sum of statistical and

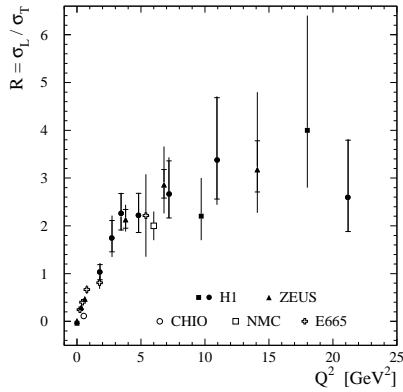


Figure 4: Measurements of the ratio of exclusive ρ^0 electroproduction cross sections for longitudinal and transverse photons, R , as a function of photon virtuality, Q^2

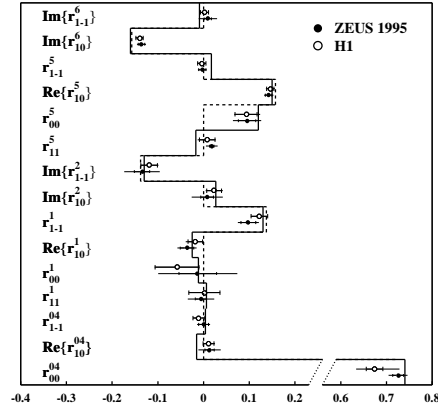


Figure 5: Combinations of spin-density matrix elements measured for ρ^0 electroproduction by the H1[?] and ZEUS[?] collaborations. See text for full description

systematic uncertainties. Also shown are the values of the coefficients predicted according to the hypothesis of helicity conservation in the s -channel amplitudes[?] (dashed line). Of particular interest is the violation of SCHC evinced in the non-zero value for the coefficient r_{00}^5 , which is manifested in the distribution in the azimuthal angle between the scattering and production planes (Φ_h). This observation implies a small non-zero single-flip amplitude for the production of ρ^0 mesons in helicity state 0 from transverse photons. Such a violation has now been reproduced in two further recent calculations based on differing assumptions.[?] These measurements show the level of violation of SCHC to be small enough that the effect of the assumption of SCHC in the earlier determinations of R is much smaller than the other sources of uncertainty in those determinations.

The H1 collaboration has recently extended their investigation to the proton-dissociative electroproduction of ρ^0 mesons,[?] verifying with similar significance that the violation of SCHC observed for the exclusive case holds also when the proton dissociates.

Preliminary results of a full decay-angle analysis with similar statistical power for exclusive ϕ electroproduction in the same kinematic region have been presented by the ZEUS collaboration last year.[?] They find values for the fifteen combinations of matrix elements consistent with those found for the ρ^0 meson, exhibiting a similar helicity violation and comparable values for R .

The ZEUS collaboration also performed the analysis[?] in the low- Q^2 region $0.25 < Q^2 < 0.85 \text{ GeV}^2$, finding a value for r_{00}^5 of similar magnitude, but also distinct indications for a more complex pattern of helicity violation, including double-flip contributions, as previously found in ρ^0 photoproduction (see Sect. 4).

Statistical limitations have precluded such full decay-angle analyses for J/ψ electroproduction; however, both the H1[?] and ZEUS[?] collaborations have published measurements of R for the exclusive electroproduction of J/ψ mesons under the assumption of SCHC. The values are found to be significantly smaller than those found for the ρ^0 at similar Q^2 .

4 Photoproduction of ρ^0 , ϕ Mesons at High Momentum Transfer

The photoproduction of light vector mesons with high transverse momenta has raised interest recently^{?,?} as a means of investigating the rôle of the momentum transferred to the proton in establishing the scale of the interaction, since the photoproduction of ρ^0 mesons at low $|t|$ has been shown to be governed by a soft diffractive production mechanism. However, diffractive photoproduction of the light vector mesons has been shown to be dominated by the proton-dissociative process for squared momentum transfers $|t| \gtrsim 0.5 \text{ GeV}^2$, well below the perturbative regime.[?] The investigation of exclusive vector-meson production at high $|t|$ requires a trigger on the elastically scattered proton and such studies at HERA have lacked the integrated luminosity necessary to measure the small cross sections at such high values of $|t|$. However, the ZEUS collaboration[?] has recently employed a photoproduction-tagging method to investigate the proton-dissociative production of ρ^0 mesons for values of $|t|$ up to 11 GeV^2 . The trigger conditions required the scattered positron to be detected in a special-purpose tungsten/scintillator calorimeter located 3 cm from the positron beam axis, 44 meters distant from the nominal e^+p interaction point in the positron-beam flight direction. The position of this photoproduction tagger determines the accepted range of energy lost by the positron to the photon which interacts with the proton, thus restricting the W range to the region $80 < W < 120 \text{ GeV}$. Since the transverse momentum of the final-state positron is thus required to be small ($Q^2 < 0.01 \text{ GeV}^2$), the transverse momentum of the ρ^0 (p_t) detected in the central detector via its dipion decay provides an accurate approximation for the square of the four-momentum transferred to the proton: $t \simeq -p_t^2$. Offline data-selection criteria include the reconstruction of exactly two tracks from the interaction vertex and reject events with calorimetric energy deposits in the rear and barrel sections of the calorimeter which are not associated with the extrapolation of either track. The selected events

exhibit a substantial rapidity gap between the dissociated nucleonic system and the two tracks. Even for the highest values of $|t|$, the decay pions are in the rear half of the central detector.

Figure 6 shows the differential cross sections, $\frac{d\sigma}{dt}$, measured for ρ^0 and ϕ mesons. These exhibit extremely hard spectra; a fit to the form $\frac{d\sigma}{dt} \propto (-t)^{-n}$ results in a value for n of approximately 3. The results are compared to a QCD calculation by Ivanov and Ginzburg[?] which estimates both perturbative and non-perturbative contributions. In this model, the non-perturbative contribution is found to account for the hardness of the spectrum and to dominate in the region covered by the measurements for the ρ^0 meson. The calculation underestimates the ϕ cross section over most of the t range covered. The comparison of the data to the calculation of the purely perturbative contribution

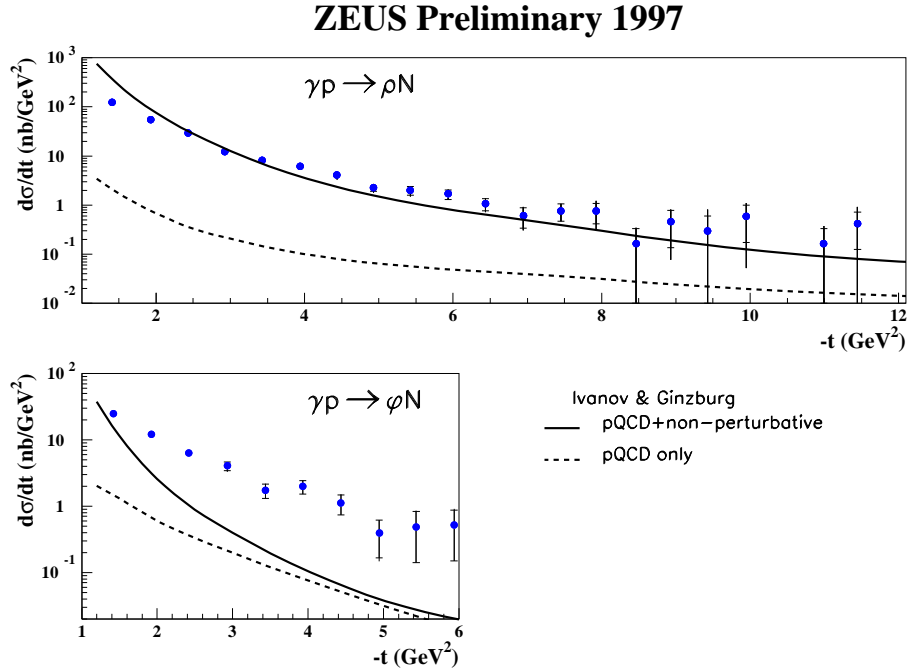


Figure 6: Preliminary measurements of the differential cross sections $\frac{d\sigma}{dt}$ for the proton-dissociative photoproduction of ρ^0 and ϕ mesons in the energy range $80 < W < 120$ GeV recently presented by the ZEUS collaboration[?] The inner error bars represent the statistical uncertainties; the outer error bars show the quadratic sum of statistical and systematic uncertainties. The results of a QCD calculation by Ivanov and Ginzburg[?] (solid line) which distinguishes the purely perturbative contribution (dashed line) are shown for comparison

alone shows a good description of the shape of the t dependence, whereas the magnitude of the cross section is underestimated by more than one order of magnitude. The model thus fails to reproduce the ratio of ϕ production to that for the ρ^0 meson at high $|t|$, which is measured to be consistent with the value of $2/9$ expected for a flavor-independent production mechanism.

The ZEUS collaboration has employed this photoproduction-tagging technique to perform decay-angle analyses of the diffractive photoproduction^{?,7} of pion pairs in the ρ^0 mass region at values of $|t|$ up to 4 GeV². In this study, the small contribution from the elastic process was not subtracted. The decay-angle distribution was parameterized in terms of combinations of spin-density matrix elements in the Schilling-Wolf convention[?], r_{ij}^{04} , as

$$W(\theta_h, \phi_h) = \frac{3}{4\pi} \left[\frac{1}{2} (1 - r_{00}^{04}) + \frac{1}{2} (3r_{00}^{04} - 1) \cos^2 \theta_h - \sqrt{2} \text{Re}(r_{10}^{04}) \sin 2\theta_h \cos \phi_h - r_{1-1}^{04} \sin^2 \theta_h \cos 2\phi_h \right], \quad (2)$$

where the three-dimensional distribution (Eq. 1) has been averaged over the unmeasured azimuthal angle between the positron scattering plane and the ρ^0 production plane, and thus no longer distinguishes the photon helicity states ± 1 .

Under the assumption that the dipion final state is produced with one unit of angular momentum, and neglecting the contribution by longitudinal photons, these combinations of matrix elements are related to the helicity amplitudes, $T_{\lambda_\rho \lambda_\gamma}$, as follows^{?,7}:

$$r_{00}^{04} \simeq \frac{|T_{01}|^2}{|T_{01}|^2 + |T_{11}|^2 + |T_{1-1}|^2}, \quad r_{1-1}^{04} \simeq \frac{\text{Re}(T_{11}T_{1-1}^*)}{|T_{01}|^2 + |T_{11}|^2 + |T_{1-1}|^2},$$

$$\text{Re}(r_{10}^{04}) \simeq \frac{1}{2} \left[\frac{\text{Re}(T_{11}T_{01}^*) + \text{Re}(T_{1-1}T_{0-1}^*)}{|T_{01}|^2 + |T_{11}|^2 + |T_{1-1}|^2} \right]. \quad (3)$$

Figure 7 shows the results for the combinations of matrix elements obtained from a least-squares minimization procedure in which they served as fit parameters. The inner error bars represent the statistical uncertainty; the outer error bars show the quadratic sum of statistical and systematic uncertainties. The systematic uncertainties are dominated by the uncertainty in the acceptance corrections. The dipion mass range was restricted to the region $0.45 < M_{\pi\pi} < 1.1$ GeV. The results are compared to the results at lower $|t|$ for the exclusive reaction obtained with 9 GeV photons from a backscattered laser

beam incident on a hydrogen bubble chamber at SLAC.[?] Also shown are the ZEUS 1994 results for exclusive ρ^0 photoproduction at low $|t|$.[?] The parameter

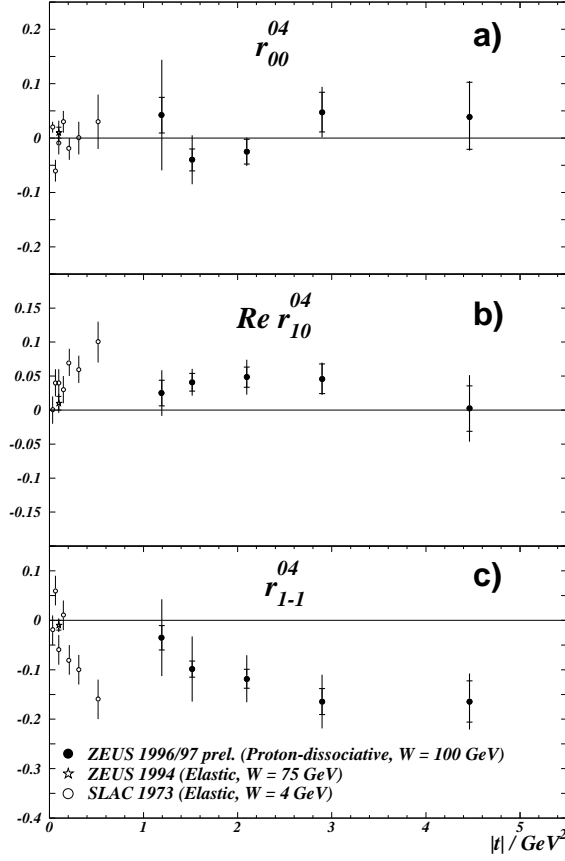


Figure 7: Recent measurements by the ZEUS collaboration^{?,?} of the combinations of matrix elements (a) r_{00}^{04} , (b) $\text{Re } r_{10}^{04}$, (c) r_{1-1}^{04} for the diffractive photoproduction of pion pairs. The inner error bars represent the statistical uncertainties; the outer error bars show the statistical and systematic uncertainties added in quadrature. See text for full description

r_{00}^{04} is consistent with zero over the entire range in $|t|$, showing no evidence for the production of ρ^0 mesons in helicity state 0. The combination $\text{Re } r_{10}^{04}$, which is predominantly sensitive to the interference between the helicity-conserving amplitude and the single-flip amplitude, shows clear evidence for a small single-flip contribution in both the SLAC data and the high- $|t|$ ZEUS results. A clear

indication of a sizeable double-flip contribution is shown by the measurements of r_{1-1}^{04} at high $|t|$, as was seen in the SLAC results at lower $|t|$ and lower energy.

In order to estimate the effect on the angular distributions of a hypothesized dipion background to ρ^0 decay, the decay-angle analysis was repeated for restricted dipion mass ranges above ($0.77 < M_{\pi\pi} < 1.0$ GeV) and below ($0.6 < M_{\pi\pi} < 0.77$ GeV) the nominal value for the ρ^0 mass. The observed value for each of the combinations of matrix elements was found to depend significantly on the mass range chosen, though the above conclusions concerning the lack of longitudinal polarization and the evidence for a double-flip contribution remain unchanged. This dependence on dipion invariant mass may suggest the presence of a non-resonant background. The extraction of the spin-density matrix elements for the ρ^0 meson alone from these dipion angular distributions thus awaits the understanding of this dependence.

The complexity of the helicity structure in pion-pair photoproduction is thus shown to persist at high values of $|t|$, where the hardness of the $|t|$ spectrum and the value of the ϕ/ρ^0 ratio encourage attempts to describe the semi-exclusive electroproduction of vector mesons in the framework of perturbative QCD.

5 Concluding Remarks

The selection of results on diffractive vector-meson production from the HERA collider experiments presented above exemplifies ongoing measurement programs undertaken by the H1 and ZEUS collaborations. The luminosity upgrade program scheduled for the year 2000 is expected to provide an increase in instantaneous luminosity of roughly a factor of five. This increase is of particular importance for investigations such as those covered above in the context of this workshop: Υ photoproduction, complete helicity analyses of vector-meson electroproduction, and semi-exclusive vector-meson photoproduction at high momentum transfer, since their accuracy is statistically limited. The future operation of HERA is therefore certain to continue to provide new results on exclusive and semi-exclusive processes at hard scales, ensuring a rigorous series of tests for new applications of quantum chromodynamics.

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References